Watersheds at Risk to Increased Impervious Surface Cover in the Conterminous United States

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Abstract: In this paper, we estimated impervious surface from United States census housing density data sets for the conterminous United States to examine the distribution and extent of impaired watersheds, and to estimate the risk to watersheds from development in the near future. We used regression tree methods to relate estimates of current housing density to the 2001 National Land Cover Database (NLCD) percent urban imperviousness. As of 2000, we estimate 83,749 km^2 of impervious surface (IS) cover across the United States (about 9.6% lower than the NLCD). We estimate that IS cover will expand to 114,070 km^2 by 2030. About 7% of eight-digit Hydrologic Unit Code (HUC) watersheds (3.6% of the conterminous United States) were stressed or degraded (>5% IS) in 2000, and we estimated that this will increase to nearly double to 8.5% of watersheds by 2030 (6.3% of area). We explored the subtle differences of fine-grain pattern for different urban land use types by comparing our national estimates of IS to those developed for the Chesapeake Bay watershed. We also found important nonlinear affects of watershed scale and aggregation, whereby estimates of IS could differ by roughly ten-fold.

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Introduction

Impervious surface can be defined as any human-produced material or activity that prevents infiltration of water into the soil. Features that commonly account for the majority (~80%) of impervious cover include buildings (e.g., roofs, driveways, and patios), roads, and parking lots (Slonecker and Tilley 2004). The proportion of a watershed that is covered in impervious surface (IS) is an integrative, comprehensive, and measurable indicator of the impacts of urban development on freshwater ecosystems and water resources (Allan 2004). This simple metric is a particularly useful indicator because it can be readily incorporated into land use planning (Arnold and Gibbons 1996; Paul and Meyer 2001; Schueler 2003).

A number of approaches have been developed to measure historical or current conditions of IS. Moglen and Kim (2007) described important differences between estimates produced from parcel land use databases (Stankowski 1972; NOAA 2002; Chabaeva et al. 2004; Reilly et al. 2004) versus land cover data from satellite imagery (Dougherty et al. 2004; Goetz et al. 2003; Homer et al. 2004; Jennings et al. 2004). Estimates of IS across broad extents (e.g., regional to national) have relied on satellite imagery, including Landsat Thematic Mapper (TM) (Homer et al. 2004, Jantz et al. 2005) and the Defense Meteorological Satellite Program (DMSP) (Elvidge et al. 2004, 2007).

Estimates of *current* IS are useful, but decision makers often desire information that will anticipate likely changes. Therefore, we wanted to develop a way to examine the watersheds that are most *at risk* to likely increases of impervious surface due to urbanization and development that may occur in the near (30 year) future. This is a goal similar to Exum et al. (2005) who used state-level population projections to develop estimates of future IS in the southeastern United States.

Building on our work that forecasts urbanization (Theobald 2001, 2005; Jantz et al. 2003), we used estimates of current and future housing density to anticipate likely changes in IS. Housing density is a stronger indicator of landscape change than population density because population estimates are typically based on permanent resident population. As a result, many areas with unoccupied, vacation, or second homes are underrepresented by population estimates (Theobald 2001). A potential weakness of estimating IS from both population and housing density data is that IS will be underestimated in areas of predominately commercial or industrial land use that often have high IS, because estimates of population and housing density are low in these areas. We directly examine the rates of under- and overestimation below.

Our overall goal in this paper was to estimate how many and which watersheds in the conterminous United States are at risk of being impacted by likely urbanization in the next 30 years. To do this, our specific objectives were to: (1) develop estimates of current IS from +current housing density based on a statistical relationship between housing density and existing estimates of IS; (2) compare our estimates to existing national and regional estimates of IS; (3) estimate likely increases in IS based on forecast housing density for 2030; and (4) identify which watersheds [i.e., eight- and ten-digit Hydrologic Unit Code (HUCs)] are currently

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stressed (exceed 5% IS) and which will likely be stressed by 2030.

We also identified and addressed two limitations of previous work on IS. First, most watershed-based analyses assume homogeneity within a watershed and no flow between watersheds. Yet, often there is strong variability of IS along the course of a river within a watershed (Moglen and Kim 2007, Goetz et al. 2008). Furthermore, almost half of the ten-digit HUCs have an adjacent, upstream HUC that flows down into the "adjoint" HUC (Maidment and Djokic 2000), which is not a "true" or "head" watershed (Seaber et al. 1987). We examined these issues by comparing IS for both the "local" and "accumulative" summaries by eight and ten digit HUCs. Note that the need to incorporate process-specific connectivity is increasingly important with finer-grained representation of landscapes, because the proportion of "true" or headwater watersheds declines rapidly with increased resolution (Table 1).

Second, when variables such as percent urban land use or IS are accumulated from "head" watersheds down to "adjoint" watersheds below through a hydrologic network that represents the topological relationships of flow connectivity, they typically are weighted proportionally to the watershed area (Peterson et al. 2007). However, weighting based on watershed area ignores the variability of stream flow or discharge, particularly in the more arid Western United States. As such, flow-weighted averaging is more logical, particularly in these arid and semiarid systems. Understanding the difference between local and accumulative estimates of IS is important to local planning actions focused on ameliorating the effects of upstream communities. Moreover, we recognize that the fine-grain pattern of land use is important in relation to specific streams and rivers within a watershed (Gergel et al. 2002; Baker et al. 2006; Goetz et al. 2008), but we were unable to explore this issue for the national assessment on which we focus.

Methods

We conducted three steps to develop national estimates of current and likely future IS. First, we developed a statistical relationship between housing density and IS. We used as our response variable the NLCD 2001 Percent Urban Imperviousness (IS_{PUI}) data set (MRLC 2007). The IS_{PUI} is produced using a categorical regression tree (CaRT) based on satellite imagery and road data sets (Homer et al. 2004). We aggregated the 30 m IS_{PUI} data set to 990 m^2 cells and then resampled using bilinear interpolation (Theobald 2007) to 1 km^2 resolution.

For our sole predictive variable, we used 1 km^2 housing density estimates for 2000 from the Spatially Explicit Regional Growth Model (SERGoM) v3 (Theobald 2005), aggregated from 1 ha. SERGoM provides estimates of housing density based on United States census block-level estimates refined through dasymetric mapping techniques (Wright 1936). Rather than sampling IS across a gradient of urbanization, we generated a spatially balanced random sample of 200,000 points from across the conterminous United States using the reversed recursive-quadrant randomized raster algorithm (Theobald et al. 2007). This allows strong statistical inference because the entire housing density gradient was represented, rather than being narrowly based on purposefully sampled urban areas.

We extracted the values of both the IS_{PUI} and current housing density (HD_{2000}) at each sample point, and used a CaRT model (Brieman et al. 1984; Friedl and Brodley 1997) to develop a relationship using the *cv.tree* function in S-Plus (Insightful Corporation, Seattle). CaRT models explain variation in a response variable by repeatedly splitting data into more homogenous groups, using categorical and/or numeric variables. They are nonparametric and can handle nonlinear relationships and high-order interactions (Brieman et al. 1984; De'ath and Fabricius 2000). We conducted a tenfold cross-validation to examine the decrease in overall deviance, but we did not prune the resulting tree because the deviance did not increase with additional nodes. The distribution of the residuals ranged from −48.04 to 88.86 (mean=0.0). This distribution is not unexpected because there are locations where $IS_{PUI}=0.0$ but $HD_{2000}>0.0$, which occurs because areas with roughly less than 1 unit per 1 ha are typically classified as the dominant land cover type (e.g., grassland) (Ward et al. 2000). Also, the large tree size (66 nodes) likely occurred because there is not a simple, linear relationship between IS_{PUI} and HD_{2000} (i.e., a poor fit; $R^2=0.38$). To generate a map of IS based on the housing density (IS_{HD}), we converted the tree into a set of if-then-else conditional statements in ArcGIS. To forecast likely imperviousness in the future, we input housing density for 2030 from SERGoM v3 into the CaRT model and generated a predicted map of IS_{HD2030}.

Second, we compared our mapped estimates of IS_{HD} back to the IS_{PUI} data set and to the Elvidge et al. (2004) data set created from a combination of National Land Cover Database (NLCD) urban classes and the DMSP nighttime lights. In an effort to develop a more detailed understanding of the patterns of potential over- or underestimation, we also compared our results to regional estimates of IS obtained for the Chesapeake Bay watershed in addition to these national data sets, following the approach used by Goetz and Jantz (2006). Because the errors in this independently derived map have been well documented (Jantz et al. 2005), it provides a spatial assessment of where the estimates derived from housing density data differ from those mapped at much finer resolution and aggregated to 1 km^2.

We also independently validated our model by comparing our IS_{HD2000} against a few "ground-truth" data sets that we were able

Table 1. Percentage of Watersheds That Are "True" Headwater Watersheds with No Flow Entering Them at Different Scales

HUC digit	Number of watersheds in conterminous United States	Percentage of headwater watersheds (%)
2	18	78
4	204	68
6	329	66
8	2,151	61
10	60,393	51

Note: We have not included additional international and interbasin flows between watersheds.

Table 2. Comparison of National Estimates of Impervious Surface (IS) for Conterminous United States

Approach	Data sources	IS area (km^2)
Elvidge et al. (2004)	DMSP 2001, NLCD 92 urban, road density	113,000
Elvidge et al. (2007)	DMSP 2001, NLCD 92 urban, road density, landscan ambient population	83,000
Homer et al. (2004)	NLCD 2001 PUI	93,000
IS_{HD2000}	SERGoM v3 Housing density 2000	84,000
IS_{HD2030}	SERGoM v3 Housing density 2030	114,000

Note: Estimates are rounded to the hundreds of square kilometers; DMSP=defense meteorological satellite program; NLCD=national land cover database; PUI=percent urban impervious; and SERGoM=spatially explicit regional growth model.

to acquire, including 80 data points generated from high-resolution aerial photography of 1 km^2 "chips" from 13 major urban centers that were used to generate the Elvidge et al. (2004) data set (IS_{DMSP}), and watersheds in Atlanta and Maryland described by Exum et al. (2005). Although these data often are purposely targeted to capture a gradient of urbanization—especially intense commercial/industrial lands—they are some of the best publicly available data sets.

Our final step was to summarize the IS_{HD} estimates by eight- and ten-digit HUC for both 2000 and 2030. There are 2,151 eight-digit HUCs, with an average size of 3,654.4 km^2 (SD=2,351.1 km^2). We generated a total of 60,393 ten-digit HUCs as catchments around river segments formed around a 1:100,000 scale RF3 hydrologic data set (Hall et al. 2000). The mean size of these ten-digit HUCs was 128.48 km^2 (SD 264.60 km^2). We classified watersheds into five classes of stress to impervious surface (similar to Slonecker and Tilley 2004; Elvidge et al. 2007): unstressed (0–0.9%); lightly stressed (1–4.9%); stressed (5–9.9%); impacted (10–24.9%), and degraded (25% and larger). In addition to the local percentage of IS, we computed the accumulated percentage of IS by watersheds using a flow-connected GIS database created by the Functional Linkage of Watersheds and Streams tools (FLoWS); (Theobald et al. 2006). We computed accumulated IS by weighting watersheds by the estimated annual streamflow (discharge) for each RF3 stream reach using the equations described by Vogel et al. (1999), rather than weighting them solely on an areal basis.

Results

Summarizing our results using eight-digit HUCs, we estimate that 83,700 km^2 in the conterminous United States (total area 7,860,700 km^2) was covered by impervious surface as of the year 2000 (Table 2, Fig. 1). Our estimate is slightly lower (9.6%) than the estimated 92,600 km^2 from NLCD 2001 (IS_{PUI}), but is bracketed by the estimates of Elvidge et al. (2004, 2007) which range from to 83,300 km^2 (2007) to 113,300 km^2 (2004). Based on the SERGoM v3 housing density projections for 2030, we estimate that over 114,100 km^2 will be covered by an impervious surface, suggesting a 36.2% increase in total IS in 30 years.

Validation of our year 2000 map against the estimates of IS developed from aerial photography data sets showed strong positive correlations, despite the fact that the air photos included commercial and industrial land uses as well as residential housing land uses. We evaluated the degree of fit by computing a simple linear regression between our estimates of IS and the values found from aerial photography datasets. For the national data set of 80 points from Elvidge et al. (2004), we obtained a fit of $R^2=0.69$; and for 56 14-digit HUCs in Frederick County, Maryland and 13 12-digit HUCs in the Atlanta metro area (Exum et al. 2005), we obtained $R^2=0.69$ and 0.96, respectively.

Comparing the SERGoM housing density for 2000 against the aggregated high-resolution IS for the Chesapeake Bay watershed showed both under- or overestimated areas relative to a map produced from Landsat TM imagery that incorporates all types of impervious cover (Dougherty et al. 2004; Fig. 2). That is, housing density-based estimates tended to provide higher values of IS in the outlying and rural areas, and lower values in more densely developed urban centers. Both of these types of differences are logical in that the estimates based on satellite imagery may miss

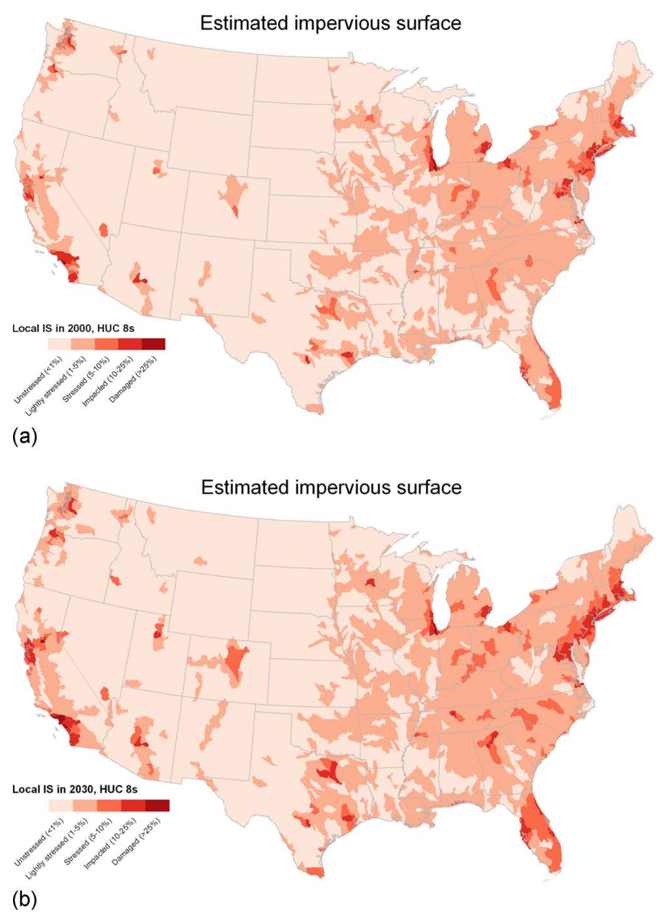

Fig. 1. Estimated impervious surface summarized by eight-digit HUCs for 2000 (a) and 2030 (b). Roughly 4.3% of the conterminous United States area is at "stressed" level or above (at least 5%) in 2000, which increases to 8.6% by 2030.

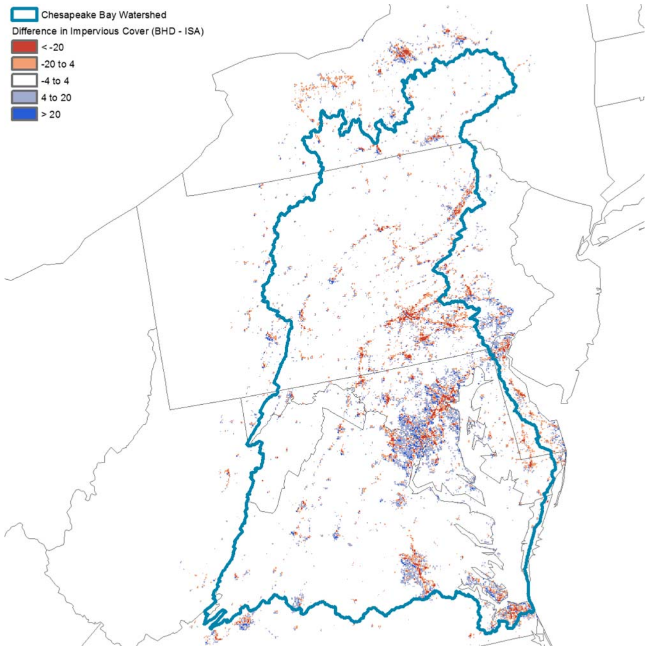

Fig. 2. Difference between impervious surface (IS) estimates derived from Census housing density (BHD) and NLCD data sets (from Fig. 1) to those from independently derived and well-validated map of IS across Chesapeake Bay watershed (CBW). Difference was calculated by subtracting CBW IS map from BHD map, thus red areas on map indicate where CBW IS exceeds BHD estimates, and blue is inverse. White areas indicate that differences in impervious cover are within ±4%.

impervious cover in less densely developed areas as a result of greater vegetation cover (particularly tree canopies) that overhang areas of impervious cover (Jantz et al. 2005, Goetz and Jantz 2006). Conversely, more densely developed central urban areas tend to contain a much higher proportion of parking lots and commercial/industrial areas that are under-represented in the housing density data sets. The total area overestimated was 7,000 km^2, the area underestimated was 7,500 km^2, with a net difference of roughly 500 km^2.

Using the housing density model estimates for the year 2000, we estimate that over 69% of the eight-digit HUCs (by area) of the United States were unstressed (<1%) by levels of IS exceeding the thresholds previously defined (see methods). Nonetheless, 26.7% were lightly stressed, 2.6% were stressed, 0.9% were impacted, and <0.1% were degraded (Table 3). By 2030, unstressed HUC-8 watersheds in the United States declined by 9%, while lightly stressed watersheds increased to 32.8%, stressed to 4.5%, impacted to 1.7%, and degraded to 0.1%.

We defined "at risk" watersheds as those that are likely to change from unstressed or lightly stressed to stressed or greater in 2030—that is, those that crossed the 5% IS threshold (local analysis). Further, we distinguished watersheds where the 2030 accumulated estimate of IS was greater than the local estimate, indicating a strong influence of upstream watershed condition in contributing to local IS (Fig. 3). For eight-digit HUCs, we found that 2.6% of watersheds were at risk (by area), and an additional 0.2% had upstream contributions. For ten-digit HUCs, we found that 2.2% of the United States was at risk, and an additional 0.2% at risk from upstream influences.

Although not unexpected, we found our results are subject to two important scaling effects that caused nonlinear, counterintuitive results. Estimated IS depends strongly on the resolution of the analytical unit used to summarize the findings (i.e., eight-digit versus ten-digit HUC), as well as whether the estimate at a HUC reflects just the condition within that HUC (i.e., local catchment) or the condition of a HUC and its upstream HUCs (i.e., both local and upstream catchments). The total area in the United States of unstressed watersheds changed from 69 to 76% using local analysis of finer-resolution (eight-digit versus ten-digit HUCs) (Table 3), yet the area that was stressed (>5% IS) increased from 0.9 to 1.3%. By 2030, we expect the stressed area to be 6.3% of the United States by eight-digit HUCs or 6.2% by ten-digit

Table 3. Levels of Impervious Surface Stress Summarized by Eight- and Ten-Digit Hydrologic Unit Codes (HUCs) Watersheds in Conterminous United States

	2000				2030			
	Local		Accumulated		Local		Accumulated	
IS Class	Number	Percent of area (%)	Number	Percent of area (%)	Number	Percent of area (%)	Number	Percent of area (%)
(a) Eight-digit HUCs (n=2,151)								
Unstressed (0–0.9%)	1,424	69.7	1,443	70.9	1,226	60.9	1,243	62.1
Lightly stressed (1–4.9%)	614	26.7	616	26.3	741	32.8	750	32.3
Stressed (5–9.9%)	73	2.6	62	2.2	112	4.5	99	4.7
Impacted (10–24.9%)	36	0.9	26	0.6	64	1.7	51	1.2
Damaged (>25%)	4	<0.1	4	<0.1	8	0.1	8	0.1
(b) Ten-digit HUCs (n=60,393)								
Unstressed (0–0.9%)	45,279	76.8	45,098	75.5	40,744	69.1	40,334	67.9
Lightly stressed (1–4.9%)	11,993	19.3	13,020	20.3	14,801	23.4	16,234	25.8
Stressed (5–9.9%)	1,666	2.3	1,305	1.8	2,565	3.4	2,198	2.9
Impacted (10–24.9%)	1,146	1.3	773	0.9	1,794	2.3	1,307	1.7
Damaged (>25%)	309	0.3	197	0.2	489	0.5	320	0.3

Note: Local specifies results tabulated for each HUC. Accumulated specifies results tabulated by averaging local results by accumulating from headwater HUCs downstream to adjacent, flow-connected, adjoint HUCs.

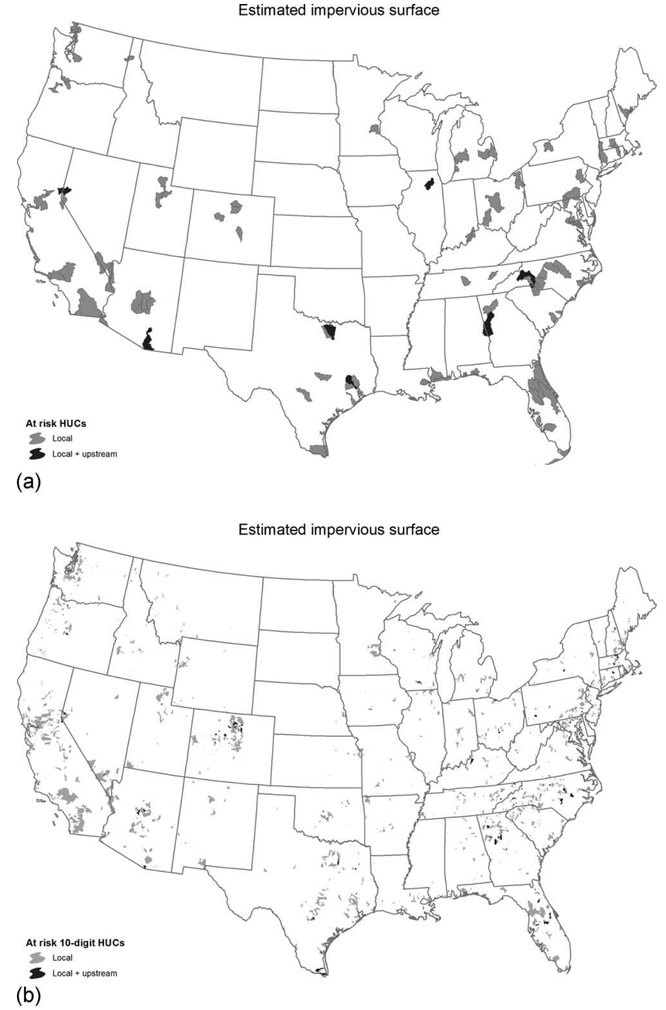

Fig. 3. Watersheds [eight-digit HUCs (a); ten-digit HUCs (b)] that are at risk of exceeding 5% impervious surface by 2030

HUCs. Using the base resolution of 1 km^2 for the $IS_{HD2000'}$ (Fig. 4), we estimate roughly 3.9% of the United States at stressed or higher levels.

Incorporating into the analysis the accumulation of watersheds (weighted by watershed area), the results also differ. Accumulated results predicted slightly less area being stressed, as compared to local-based analysis; 2.9% in 2000 and 6.0% in 2030 at the eight-digit HUC, versus 2.9% in 2000 and 4.9% in 2030 at the ten-digit HUC.

To illustrate these scaling effects, Fig. 5 shows results for an area around Denver. All of the tributaries that flow into the South Platte in the Denver metro area are "stressed," yet the accumulated value of IS for the main stem of the South Platte was only lightly stressed ($<5\%$) in 2000 because the majority of water in the stream has originated from unstressed watersheds upstream. As the South Platte flows out into undeveloped and only lightly stressed (local) watersheds downstream, its burden from the developed area is slowly diluted downstream by waters from undeveloped watersheds.

Discussion

It is not surprising that our estimates of IS were slightly (9%) lower than IS_{PUI}. Because housing density is based on residential

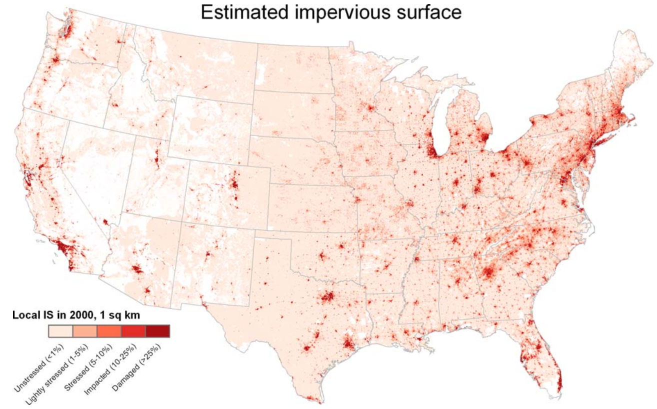

Fig. 4. Estimated impervious surface at 1 km^2 for 2000. Roughly 3.9% of conterminous United States area is at "stressed" level or above (at least 5%). Public lands are shown in white.

land use, it does not capture intense built-up land use on public lands, nor does it capture well private commercial and industrial land uses, particularly in central parts of cities where the resolution of our housing density dataset (from census blocks) is small. To complement the housing density-based estimates, we filled in the IS values at locations of IS_{HD} with IS_{PUI} values where $HD_{2000}=0.0$. These under-represented locations are mostly associated with either highways or other developed portions (e.g., visitor centers, military bases) that run through public lands or are land uses on rural private lands such as power plants, airports, or other remote commercial uses. Our estimate of $IS_{HD2000'}$ increased to 87,700 km^2 (5.3% lower than IS_{PUI}). A further logical refinement of our methods is to complement $IS_{HD2000'}$ with better estimates of IS for commercial/industrial areas where housing density is known to be low. We replaced larger values of IS_{PUI} only in commercial/industrial areas to $IS_{HD2000'}$, and our estimates of $IS_{HD2000''}$ increased slightly to 97,200 km^2 (4.9% greater than IS_{PUI}). In stand-alone uses of IS (not accounting for potential changes in the future), we used $IS_{HD2000''}$ because it is a more complete and comprehensive estimate of IS that represents all locations, urban and rural, public and private, residential and commercial.

Our results, as well as those from any regional/national-scale effort to quantify IS, should be interpreted with the limitations noted above. Fine-grained patterns and features—such as road types, on-site treatment and holding ponds, and storm water drainage systems—are important but difficult to capture in an analysis that aggregates across relatively large spatial units like HUC-8 or HUC-10 watersheds (Snyder et al. 2005). These finer grain features have the potential to modify the impervious surface estimates and their hydrological significance. For the work presented here, we necessarily had to generalize these finer scale features in order to focus on a national scale assessment. Future work may allow us to refine these estimates and better quantify the influence of impervious cover on watershed attributes, particularly watershed impairment.

Conclusion

Our estimates of impervious surface compare well to other national and regional scale estimates, and are supported by available validation data sets. Our estimates tend to under-represent IS in areas with commercial and industrial land uses. Our results sug-

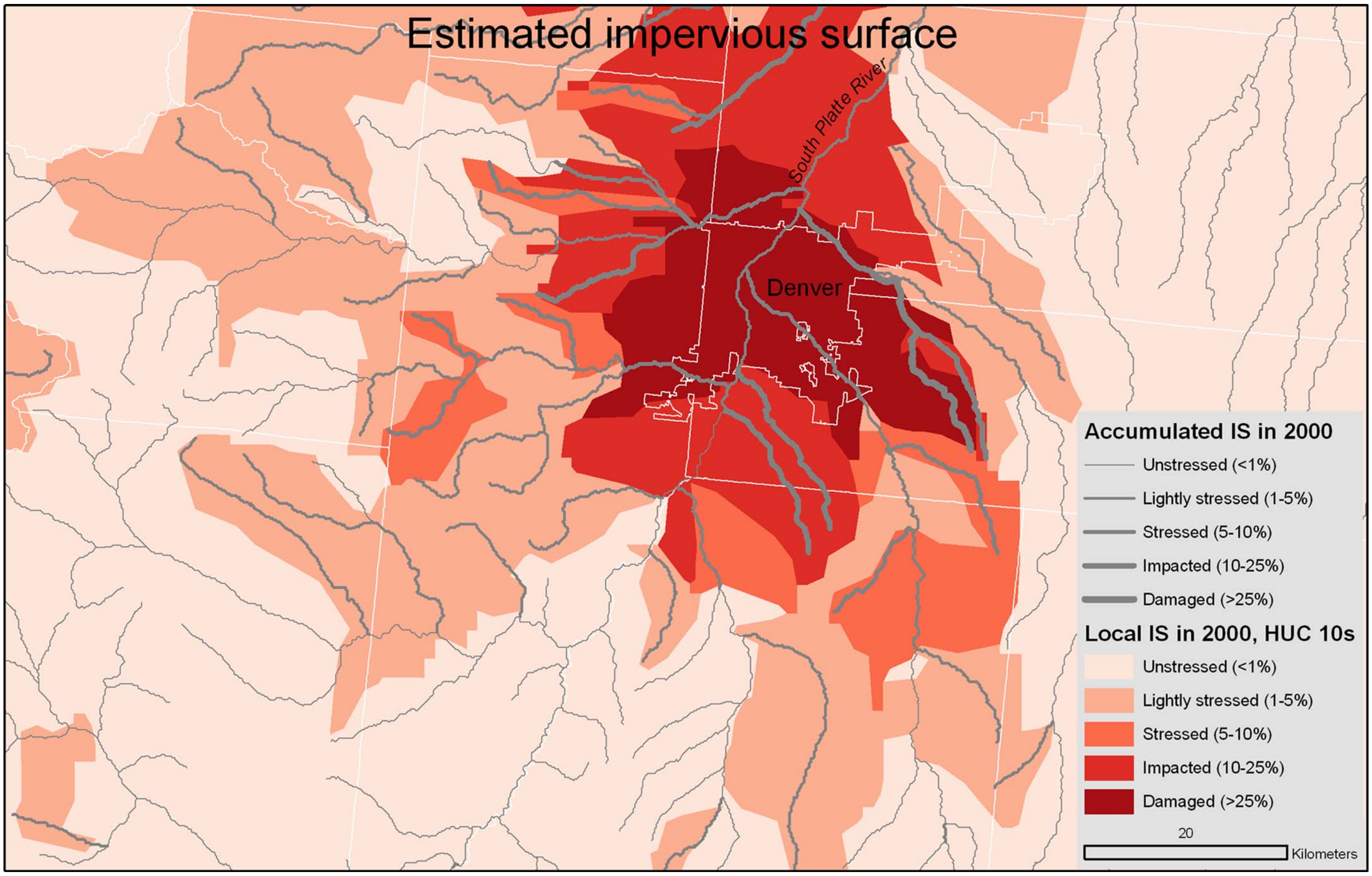

Fig. 5. Illustration of scaling effects of impervious surface results in Denver, area. Local impervious surface (IS) values are displayed for ten-digit HUCs, with accumulated IS values depicted by rivers on top. For headwater streams (map scale 1:1,000,000), local and accumulated IS is same (e.g., Big Dry Creek=25.41%, lower center). As river joins with another stream, IS may increase or decrease sharply (e.g., Big Dry Creek drops to 1.71% when it joins larger South Platte River).

gest that in 2000 over 83,700 km^2 of conterminous United States was covered by IS, which will likely expand to over 114,100 km^2 by 2030 (an increase of 36.2%). The forecast estimates are likely to be conservative since they do not incorporate expansion of commercial and industrial land uses. We estimate that roughly 3.6% of the United States is stressed from IS, which will nearly double by 2030. For mapping current conditions, we relied upon a hybrid data set ($IS_{HD2000''}$) that combined the IS_{PUI} and IS_{HD2000} to better account for both commercial and industrial land use, as well as development on public lands. Using this hybrid data set indicated that 97,200 km^2 of the United States is currently covered by IS.

We also demonstrated two important scaling effects that need to be considered when interpreting results of IS work. Estimated IS depends strongly on an analytical unit used to summarize results, and in general we find that the proportion of stressed area declines with finer-scale analytical units. Furthermore, incorporating into our analysis the simple hydrologic fact that water flows downstream and is thus subject to both dilution and concentration of chemical constituents, we found important differences relative to a more locally based analysis. Generally, accumulated results predicted slightly less area impacted at a level of stress or above. Moreover, we emphasize that accumulation should be weighted based on streamflow rather than simple watershed area. Finally, we encourage the development of a national spatial database providing IS estimates derived from high-resolution imagery, based on a consistent interpretation method and probability-based sampling approach. Such data sets would enhance the type of analyses we report on here, allowing for more refined estimates of watershed impairment going forward.

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